SEA AND LAND TESTS OF LONG-BASELINE KINEMATIC GPS INDICATE SUB-DECIMETER-LEVEL PRECISION

by

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ABSTRACT

Post-mission, long-range kinematic GPS with carrier phase, as implemented by the first author, was evaluated in both at-sea and on-land tests.
The outcome of the tests indicate an overall 3-Dimensional r.m.s. precision ("one sigma" expected error) in post-processing, over several hours, of better than one part in 10,000,000 for baselines longer than 450 km. Results were similar using either the final IGS SP3 ephemeris for the days of the experiments, or the predicted orbits broadcast in the GPS navigation message. Corrections to the broadcast orbits (when used), as well as ionospheric-free phase biases and tropospheric zenith delay mismodeling, were all estimated simultaneously with each trajectory.

1. INTRODUCTION

1.1 Technique

Operations at sea often take place far from land. Far from any GPS reference sites, L1 and L2 carrier-phase ambiguities often cannot be resolved on the fly as exact integers, but have to be estimated by the approach known as "floating" [Loomis, 1989]. Real-valued biases in the ionosphere-free combination of L1 and L2 (or "L3") are solved for along with the trajectory. The effect of errors in reference station position, satellite orbits, and tropospheric refraction corrections, do not cancel out between distant receivers. Additional unknowns, representing those errors, must be solved jointly with the L3 biases and the trajectory of the vehicle. The differential effect of the solid earth tide must be included. These questions also arise in the static, geodetic positioning of sites of world-wide networks such as that of the International GPS Service (IGS), with techniques that routinely achieve long-baseline precession of a few parts in 100,000,000 [Kleusberg and Teunissen, editors, 1998]. Such precise, long-baseline techniques can been combined with kinematic GPS, to obtain highly accurate instantaneous positions of vehicles without a detailed knowledge of their often complex dynamics [Colombo, 1991]. Such a combination may enable more effective use of remote-sensing data requiring precise geographic registration, such as altimetry, interferometric SAR, synthetic aperture radar, or sonar, collected during large-area surveys of polar regions, oceans, deserts, or continental shelves [Colombo et al., 1995]. Another application could be the validation of precise guidance systems.

While sharing a common foundation with real-time, meter-level, pseudo-range-based Wide Area Differential GPS methods [Brown, 1989], the technique tested in this study is meant to achieve decimeter-level accuracy through post-processing (or post-mission) analysis, using double-differenced, dual-frequency carrier-phase. The pseudo-range is used primarily during the initial cleaning-up and editing of data, and to obtain the initial estimates of vehicle positions, clock errors, and L3 biases. As an option, the pseudo-range may be used in the precise solution, in combination with the carrier phase. This option was not used for this work because unmodeled systematic errors in the pseudo-range (probably because of degradation caused by Anti-Spoofing, or "A/S) did not help achieve the high level of accuracy desired.

One of the main differences between short-range and long-range DGPS is the decrease in the number of satellites in common view between the vehicle and the reference stations. This decrease is made more pronounced when satellites at very low elevations are screened out to avoid excessive problems with atmospheric refraction and multipath. For distances of more than 500 - 800 km (depending on the latitude of the area surveyed, and on the number and distribution of reference stations) there may be periods of time with too few satellites in view. Since in long-range navigation it is necessary to solve simultaneously for many more parameters than the coordinates of the moving antenna and receiver clock errors, at least five satellites in common view are needed, one more than for short-range DGPS. This problem may be solved, or at least ameliorated, by using several properly placed reference stations. The total number of satellites in common view is likely to be larger with all sites combined than with any of them alone.

1.2 Software

The test data were analyzed using software developed by the first author. The main features of the software include: precise kinematic and static geodetic solutions, multiple baselines, stop-and-go kinematic, rapid static, station re-occupation, on-the-fly ambiguity resolution (short baselines), ambiguity floating (long baselines), recursive precise analysis (Kalman filtering and smoothing) with data compression for greater computing efficiency, and the optional use of a different sampling rate (slower than the rover's) for the fixed receivers. GPS data files are read in the international RINEX format. It requires a workstation, or a fast PC, and a FORTRAN 77 or 90 compiler. It runs equally well under UNIX and Windows.

2. ACCURACY TESTS

2.1 The Euro-O Platform Test

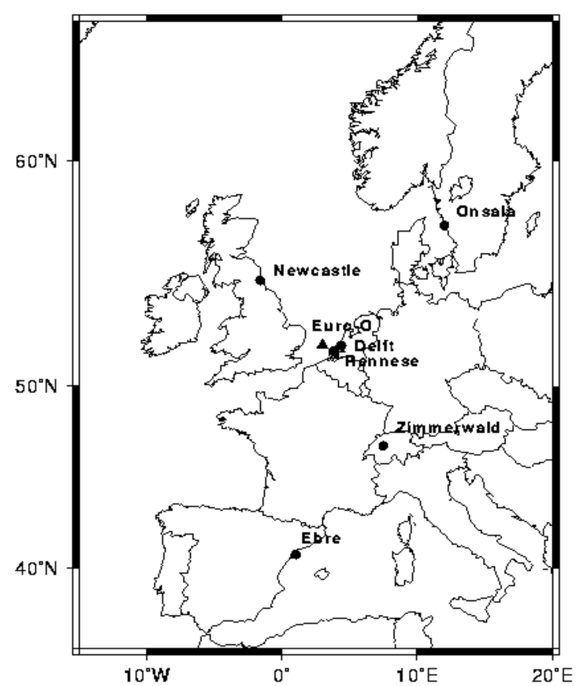

Figure 1. The locations of the Euro-O platform and reference sites in Western Europe.

This test took place on 17 December, 1996, approximately between 9:30 and 13:30 GMT. It was planned and conducted by colleagues from the Geodetic Computing Center (LGR) of the Delft University of Technology, and from the Surveying Department of the Rijkswaterstaat. The main organizers were Mr. George Husti (LGR) and Mr. Alex Damhuis (Rijks-waterstaat), in collaboration with several European universities. The reference GPS receivers were located at distances ranging from 40 km to more than 1000 km. The "rover" was either of two receivers on the Euro-O platform, in the North Sea. All were commercial dual-frequency receivers (Trimble SSI or Ashtech ZXII), operating at 1 Hz.

The Euro-O platform has been stabilized with a suspended 20,000 kg weight. It oscillates with a period of ~ 4 seconds and an amplitude unlikely to exceed 10 cm, exempt in severe storms. Conditions were relatively mild at the time of the test, and the kinematic navigation of either receiver antenna showed movements of about 5 centimeters. Since the actual movement of the platform was so small, the instantaneous kinematic location of the site was compared, at every epoch, to its mean position determined to an accuracy of a few centimeters with a static adjustment (and regarded as “truth”). The marine conditions, with high humidity, and signal multipath caused by reflections off the sea and the structure, were probably not too different from those on a large ship.

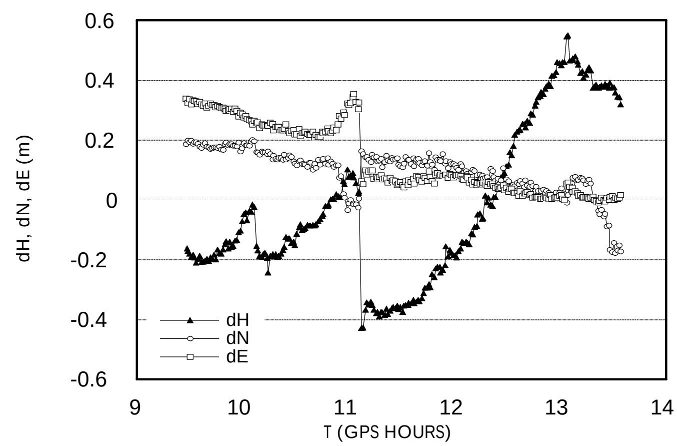

Figure 2. Height, East, North departure (in meters) from the precise static coordinates of HDEK, of a kinematic solution using *broadcast* ephemeris and relative to ONSA (818 km) and Ebre (1260 km).

For three of the land sites, Ebre, Onsala, and Zimmerwald, precise European Reference Frame (EUREF) coordinates were available from a weekly solution for GPS Week No. 884 (courtesy of Dr. Hans van der Marel). The two sites on the Euro-O platform were on a balustrade (BALU), and on the helicopter deck (HDEK). For the static positioning of the platform, the fiducial site was in Delft, about 76 km from the Euro-O platform. This distance was short enough to rule out any significant influence of possible errors in the precise GPS SP3 ephemeris used (final IGS orbits). The differential PDOP ranged from 3 to 7.

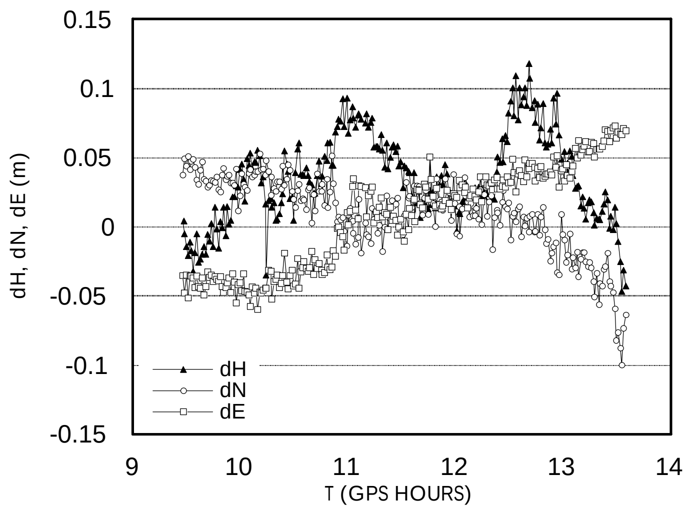

Figure 3. As in figure 2, but with *broadcast* orbits adjusted as part of the solution, and a marked improvement in accuracy.

Figures 2-4 show, at 1-minute intervals, the discrepancies in height, east, and north between: (a) a kinematic trajectory for the HDEK receiver, relative to Onsala and Ebre, 818 km and 1260 km away, and (b) the mean coordinates for that receiver, as found by static adjustment. Values are plotted every minute.

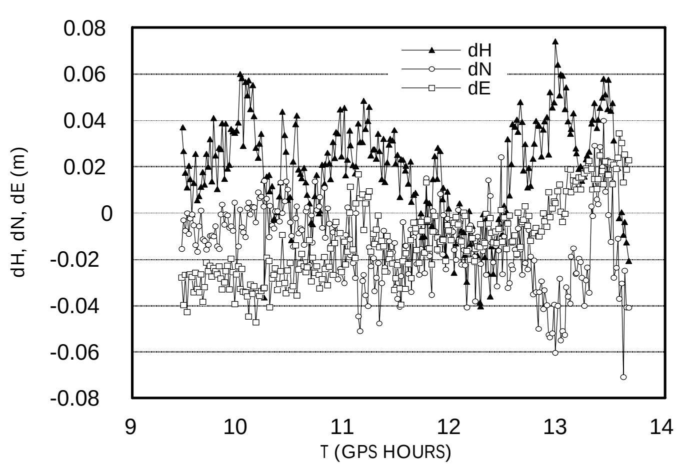

Figure 4. As in figures 2-3, with uncorrected SP3 orbits.

Figure 2 shows the instantaneous discrepancies when using the broadcast ephemeris from the GPS navigation message. Figure 3 shows the results of a similar solution, with the errors in the broadcast orbits estimated along with the trajectory. The improvement in accuracy is clear. Figure 4 shows the results when using the precise SP3 orbits from the IGS (not corrected)

By correcting the broadcast orbits as part of the navigation solution, it becomes possible to obtain a precise trajectory in near-real time, and use this for an accurate preliminary analysis of the data in the field. This could save time and wasted effort, because problems can be spotted before it is too late.

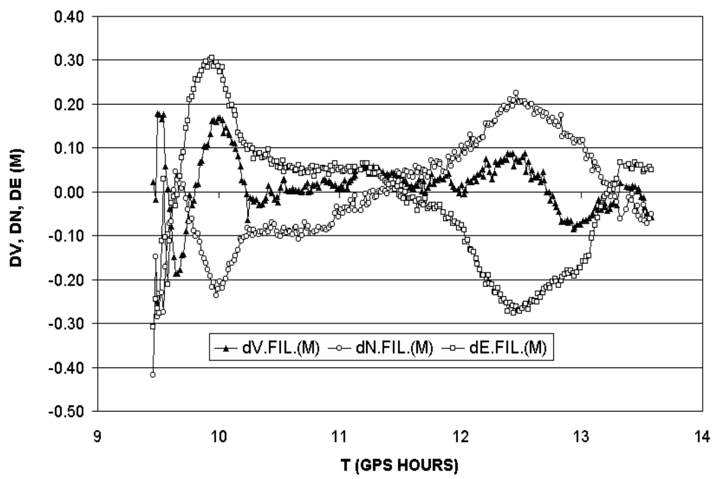

Figure 5. As in Fig. 3, Kalman filter-only solution with broadcast ephemeris (comparable to a real-time solution).

Figure 5 shows the Kalman filter-only results of the filter-smoother solution of Figure 3, with the broadcast orbits used while estimating their errors. This mimics a “real-time” calculation. Increases in the discrepancies happen when data from one or more satellites become available for the first time, and are accentuated by poorer geometry around 10 and 12:50 hours. It takes 20 to 45 minutes before the filter can make precise estimates of the floated ambiguities. Only then precise positioning becomes possible. Moreover, the accuracy of a post-processed solution cannot exceed the best accuracy of the filter alone.

The analysis of several combinations of baselines show that the r.m.s. of the 3-dimensional position discrepancies is nearly-independent of baseline length: here around 4.5 cm (as shown in Table 1 below). This suggests that relative accuracy (error/shortest baseline length) is inversely proportional to distance. Beyond 450 km, the relative accuracy of these results appears better than 1 part in 10^7. Since there is no reason to assume a significant correlation between the actual kinematic error and the slight movement of the antenna, the actual rms error should be somewhat better than that of the discrepancies shown here.

TABLE 1

Baseline Error Statistics:
(Number of 1 Hz epochs: 15200). IGS SP3 fiducial orbits, unless otherwise noted.

TUD18 -> HDEK
(76.6 km)
Mean r.s.s. 3.45 cm
r.m.s. about mean 2.56 cm
Max. r.s.s. 8.85 cm.
Total r.m.s. 4.30 cm
(5.6 parts in 10^7)

BEDS, ZIMM -> HDEK
(463.9 km, 645.1 km)
Mean r.s.s. 3.42 cm
r.m.s. about mean 2.85 cm,
Max. R.S.S. 11.58 cm
Total r.m.s. 4.45 cm
(9.6 parts in 10^8)

ONSA, EBRE -> HDEK
(SP3 Orbits)
(818.0 km, 1258.4 km)
Mean r.s.s. 2.71 cm
r.m.s. about mean 3.17 cm
Max. R.S.S. 9.58 cm
Total r.m.s. 4.17 cm
(5.1 parts in 10^8)

ONSA, EBRE -> HDEK
(Adjusted Broadcast)
(818.0 km, 1258.4 km)
Mean r.s.s. 3.8 cm
r.m.s. about mean 5.6 cm
Max. R.S.S. 14.3 cm
Total r.m.s. 6.8 cm
(8.3 parts in 10^8)

2.2 Land Test at Holloman AFB

This test took place on 8 November 1996, and it was organized by the second author and colleagues at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD), of the US Navy. For several hours in the evening of the 7th and the early morning of the 8th, local time, a pick-up truck carrying the roving receiver was driven slowly several times up and down some 30 km of an L-shaped service road in the proving grounds near Holloman AFB, in southern New Mexico. Along this way there are several survey markers on the ground, put there to position equipment that registers various tests carried in the area. The reference sites actually used were: one nearby, at Holloman (HOLO, 2-20 km from the truck in a straight line), and two distant ones: At Platteville in northeastern Colorado (PLAT, 796 km), and at the Naval Post-Graduate School in Monterey, California (NPG) 1470 km).

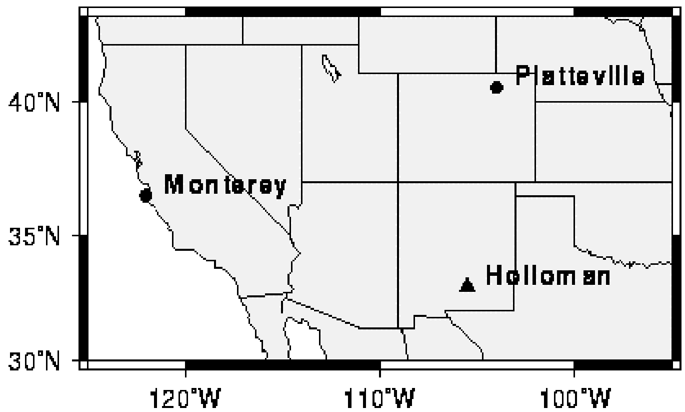

Figure 6. Locations of the test site Holloman and the two reference sites in Monterey and Platteville, in the Southwest of the U.S.A.

The coordinates for HOLO and NPG were calculated by Dr. Tomas Soler and colleagues, at NOAA, working in collaboration with Mr. James P. Cunningham at NSWCDD. (During a separate study [Cunninham et al., 1998], Cunningham and colleagues found the position for Holloman within 3 cm of NOAA's.) The coordinates for PLAT were found by the first author, using as fiducials NPZ and several IGS sites in the Southwestern US. The receivers were all Ashtech ZXII's, recording at 1 Hz.

The idea behind this on-land test was to take advantage of the possibility of occupying markers at known locations. As the vehicle reached each marker, it would stop and an operator would remove the antenna of the receiver from the truck and carry it to the marker, occupying it for about five minutes. After that, the antenna would be taken back to the truck, made secure, and the drive would then continue to the next marker. Eventually, as the vehicle turned back and returned along the same road again and again, markers would be occupied repeatedly, at intervals of about 2.5 hours.
Using for the fixed sites HOLO and NPZ the coordinates obtained from NOAA, and for PLAT our own tie to the IGS (explained earlier), two separate solutions were made: (a) a local kinematic survey relative to HOLO, (b) a long-range survey relative to NPZ and PLAT. The data for (a) and (b) were taken at different times during the same test, so there were no observations common to the short- and long-range

positioning of the truck. In each case, a continuous kinematic survey was made, regardless of whether the truck was moving or not, and only the kinematically obtained positions for the markers (at the start of each 5-minute setup), corrected for earth tides, were later compared.

TABLE 2

Differences (meters) in Marker Positions Between the Independent Long- and Short-Range Solutions.
Time in Seconds of GPS Week 878. “dP” is the 3-D r.s.s.

SITE,	dH	dN	dE	dP	TIME
ST63,	.00	.04	.02	.04	433410
ST12,	.02	.05	.02	.06	434090
ST64,	.01	.04	.04	.06	434730
PBM2,	.06	.03	.04	.08	435770
ST75,	.03	.03	.02	.05	436630
PBM2,	.07	.07	.03	.11	440320
ST12,	.10	.06	.03	.12	441860
ST11,	.12	.03	.04	.13	443310
ST63,	.07	.03	.04	.09	444250
ST64,	.04	.03	.06	.08	445110
PBM2,	.08	.04	.07	.11	445990
ST75,	.06	.05	.06	.10	446810

Table 2 shows the differences between positions of the markers obtained in the separate local and long-range kinematic solutions. To verify the short-range solution procedure, Dr. Bruce Hermann (NSWCDD) did an independent calculation analyzing the same truck and Holloman data using kinematic software with on-the-fly ambiguity resolution.

CONCLUSIONS

The kinematic positions calculated with the long-range techniques and software tested here appear to be within 10 cm of the true positions, most of the time. The 3-D r.m.s. accuracy is less than 10 cm. For baselines of more than 450 km, this is better than 1 part in 10^7 of the length of the shortest baseline used. Such results depend on having more than four satellites in common view, and favorable geometry.

Good results may be obtained using broadcast GPS ephemeris, if their errors are estimated as part of the kinematic solution. This might help during a remote-sensing campaign, by making possible precise quick-look results in the field.

For precise navigation with long baselines, more than 30 minutes may be needed to initialize floated ambiguities at the start of a session or after a major loss of lock.

ACKNOWLEDGMENTS

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The first author did most calculations during a recent stay as Visiting Professor at the Delft University of Technology, the guest of Prof. Peter Teunissen. During this stay, his work was supported with University funds, and with funds provided by the Royal Academy of Sciences of the Netherlands (KNAW) through the Netherlands Geodetic Commission. Especial thanks to Dr. Hans van der Marel.

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